

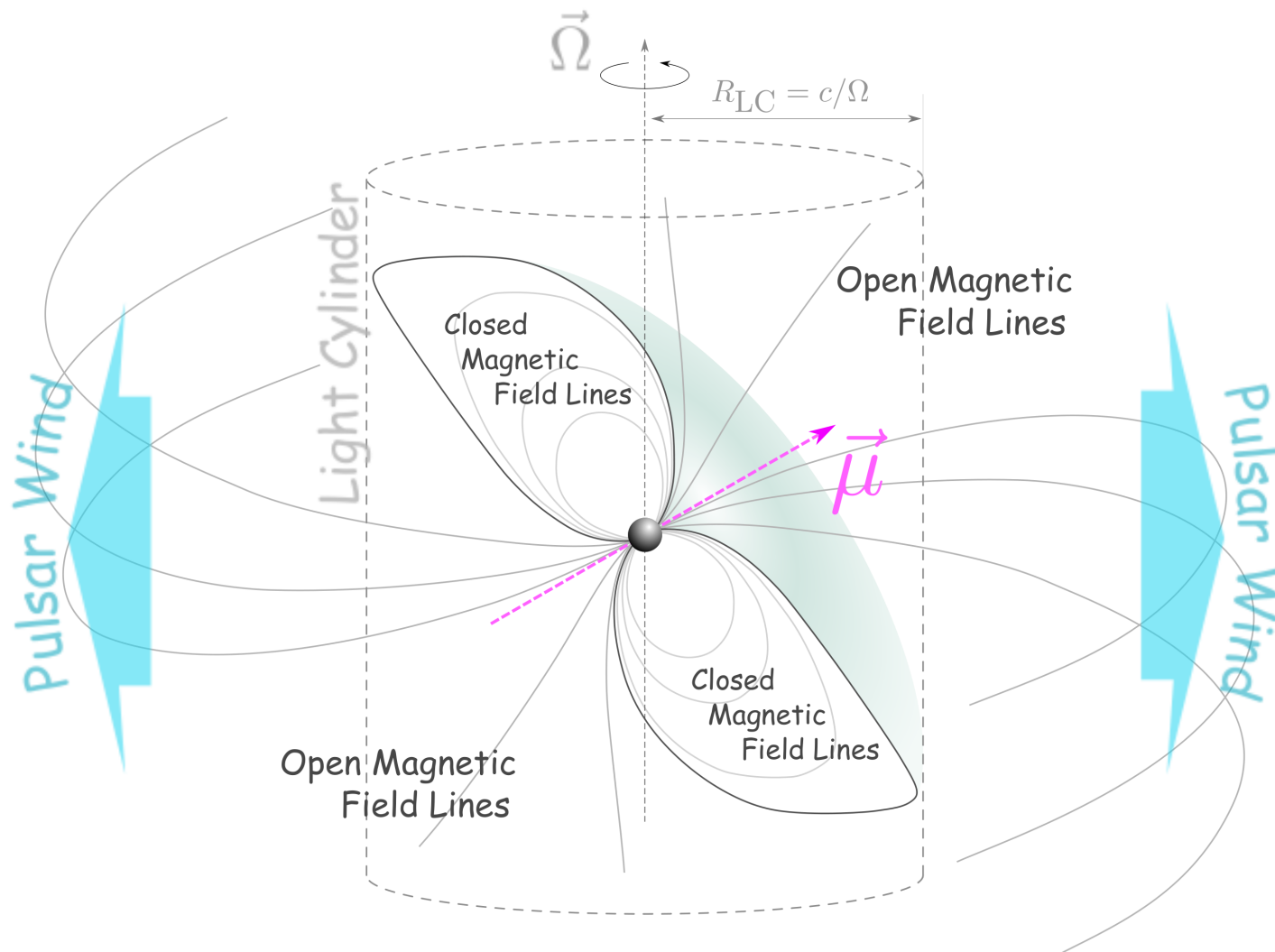
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# Non-stationary electron-positron cascades

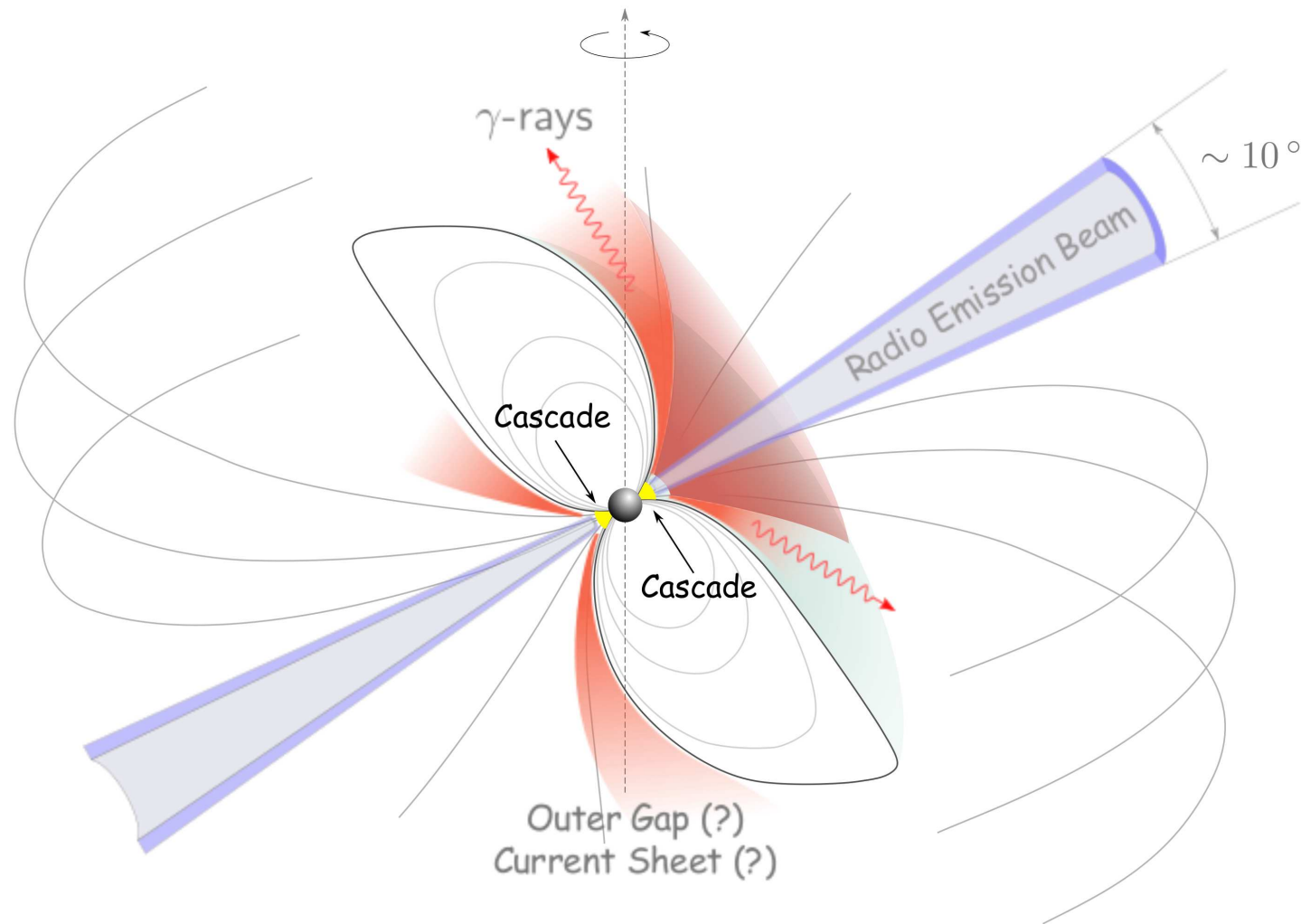
A.N. Timokhin  
University of California, Berkeley

June 21, 2010

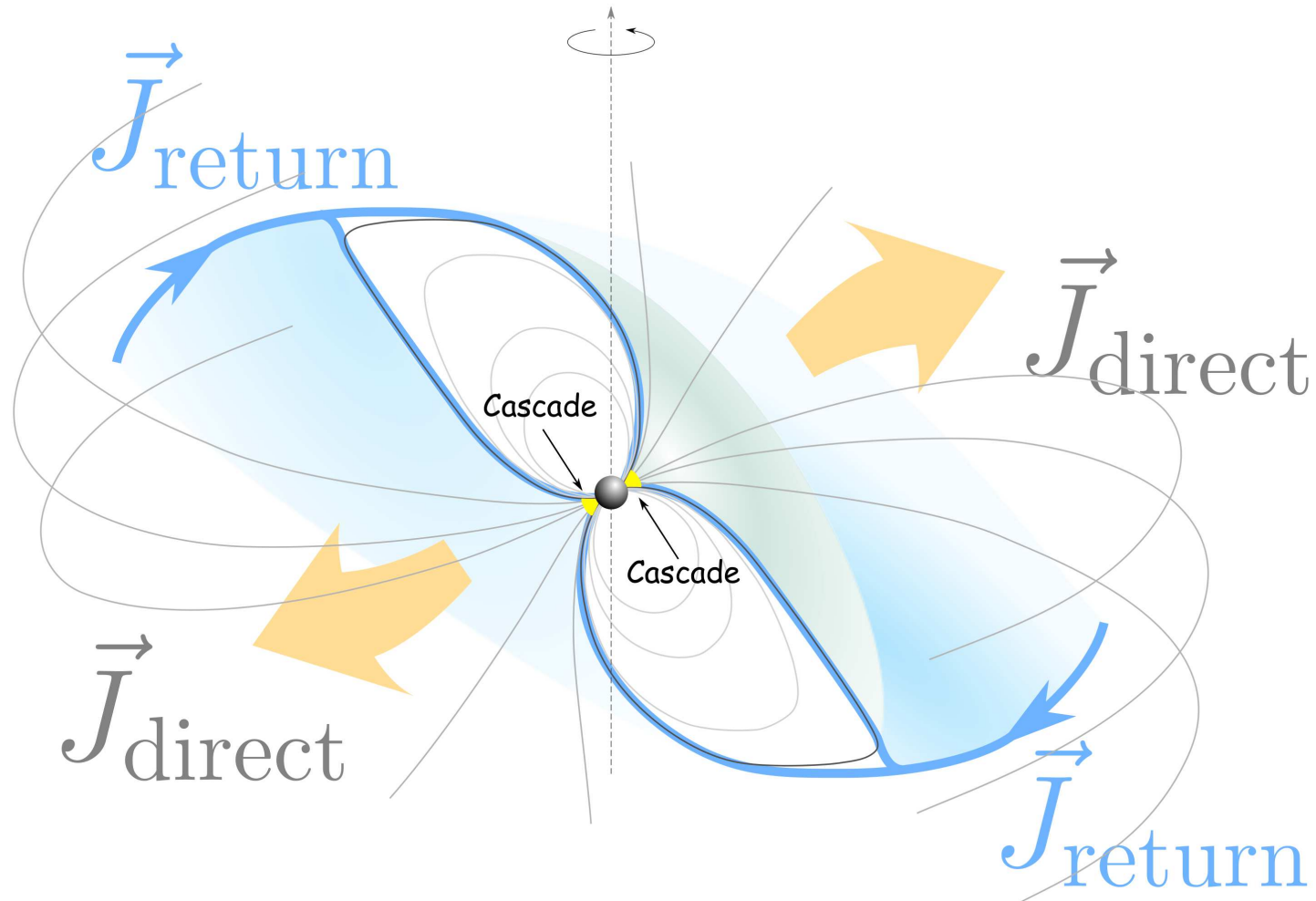
# Pulsar Magnetosphere: “Large scale view”



# Pulsar Magnetosphere: “Observer’s view”



# Pulsar Magnetosphere: “Theorist’s view”



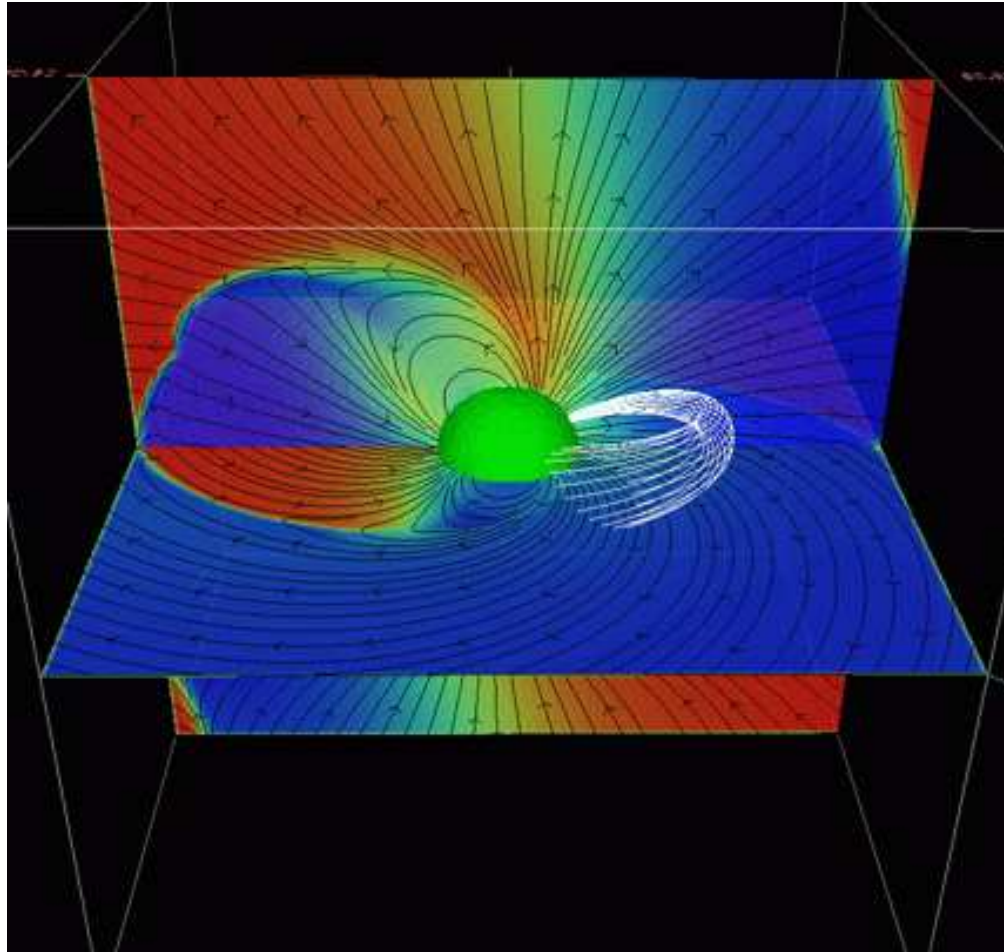
**Magnetosphere**

Enables smooth particle outflow → Sets the current density

**Polar cap cascade**

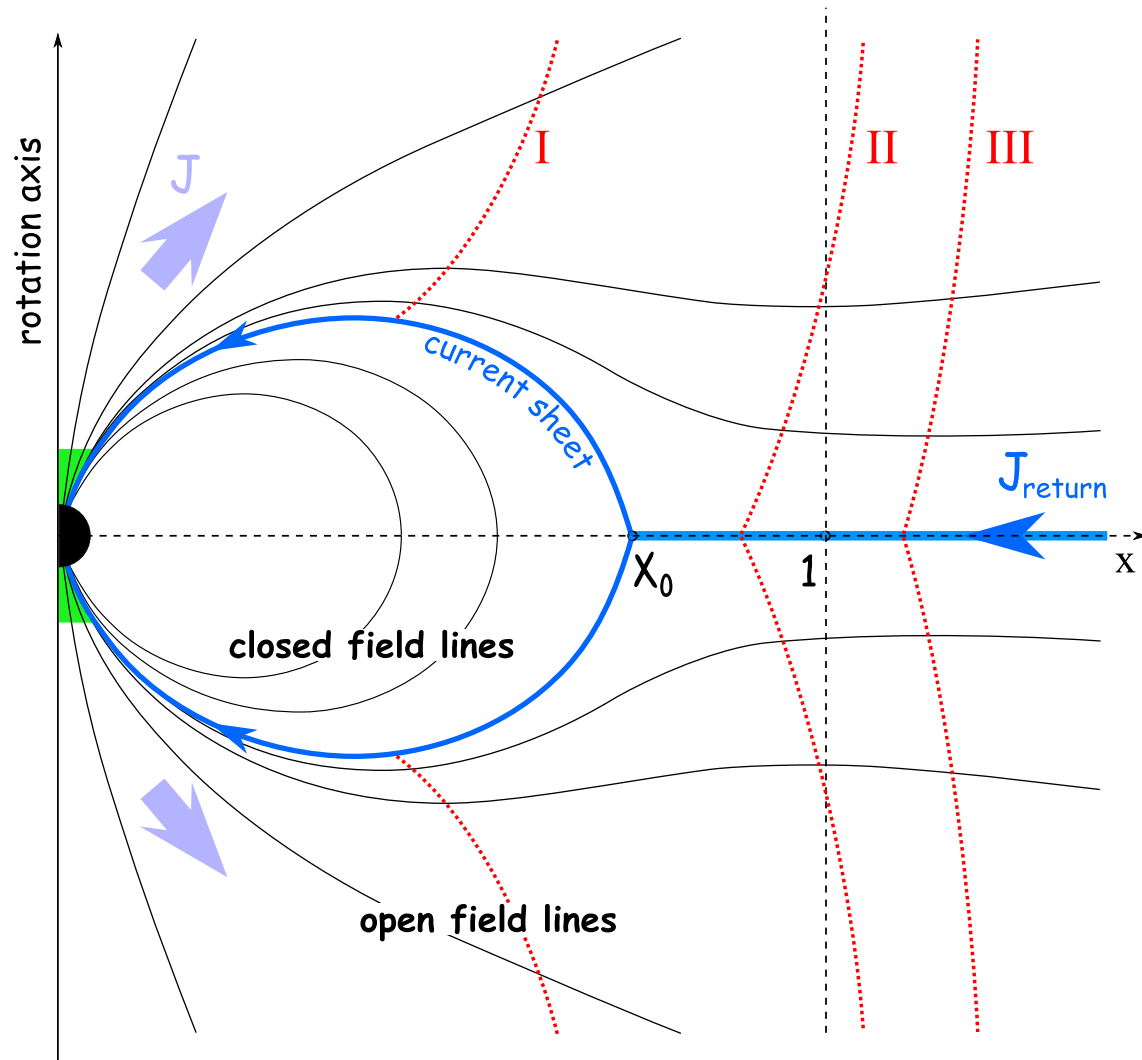
Supplies magnetosphere with plasma; Is part of the global electric circuit

# Force-free magnetosphere: 3D Numerical Model



(Spitkovsky 2006)

# Aligned Rotator-the simplest possible case



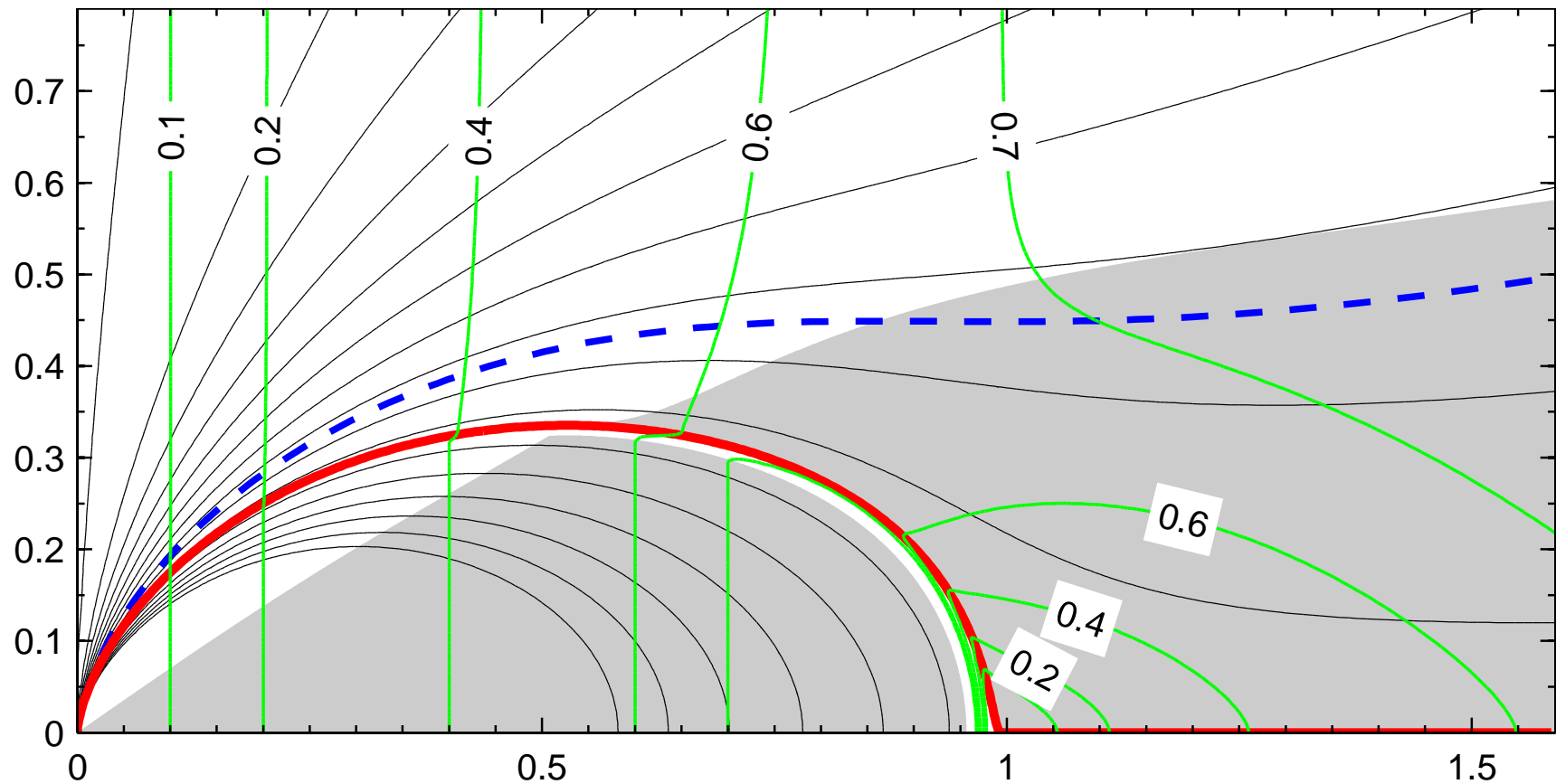
Free parameters of the model:

- Size of the corotating zone  $x_0$ :  
How many field lines cross the Light Cylinder
- Angular velocity of the open magnetic field lines

$$\Omega(\psi) = \Omega_{\text{NS}} \left( 1 + \frac{dV}{d\psi} \right)$$

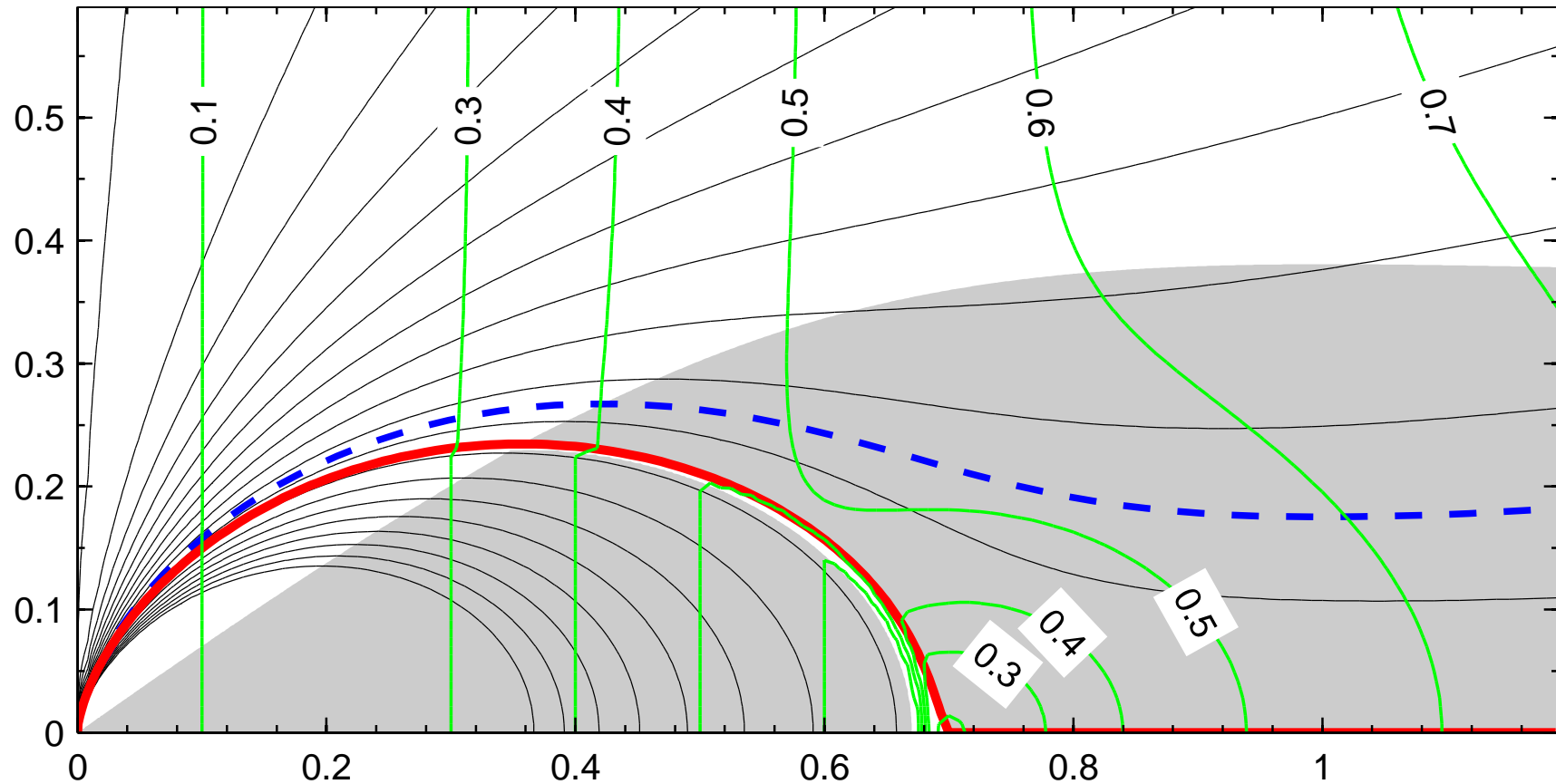
Shape of the Light Cylinder

# Magnetosphere with $\Omega(\psi) = \Omega_{\text{NS}}$ : $\chi_0 = 1$



(Timokhin 2006)

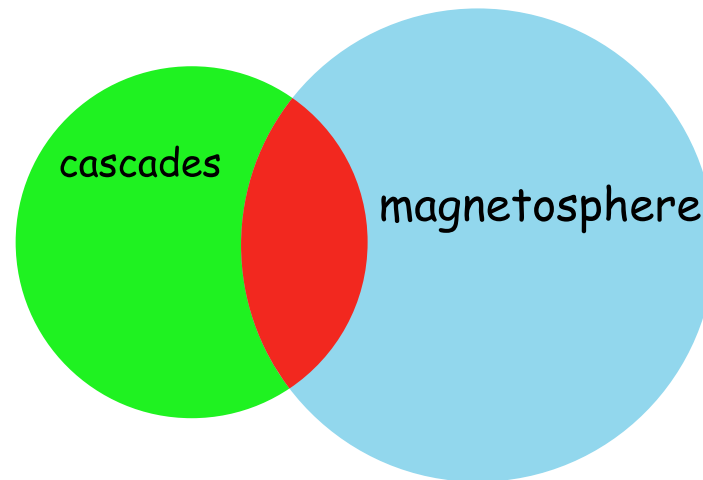
# Magnetosphere with $\Omega(\psi) = \Omega_{\text{NS}}$ : $\chi_0 = .7$



(Timokhin 2006)

# Force-free magnetosphere vs. polar cap cascades

- Force-free magnetosphere cannot exist without electron-positron pair production in the polar cap
- The same magnetospheric current flows through the cascade zone
- Pair creation is a process with a threshold. It is not obvious that any current density can flow through the cascade zone

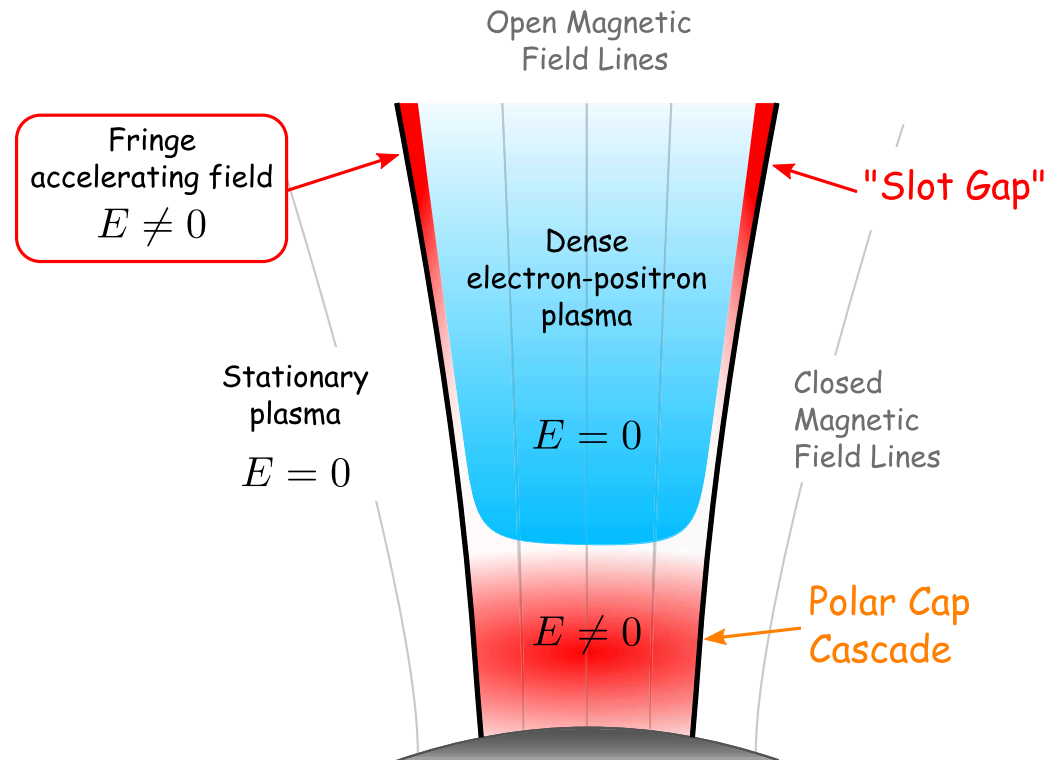


# Stationary cascades

*Arons & Scharlemann '79, Daugherty & Harding '82*

*Muslimov & Tsygan '92, Muslimov & Harding '98, Hibschan & Arons '01*

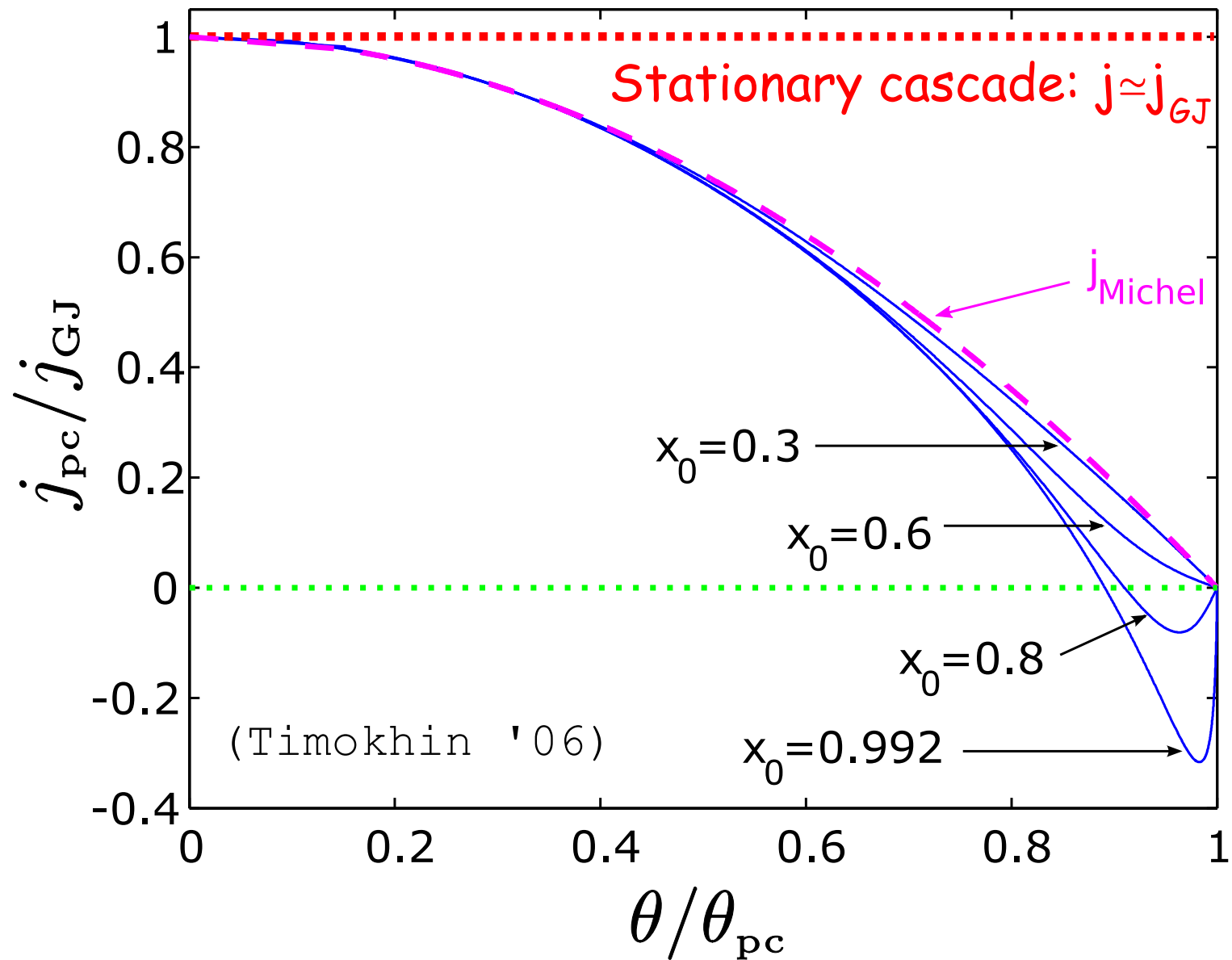
**Underlying assumption:** Stationary unidirectional particle flow



Predictions:

- Current density is almost equal to the Goldreich-Julian current density
- Potential drop in the cascade zone is very small  $\sim 1 - 2\% V_{\text{vac}}$

# Current density in the polar cap

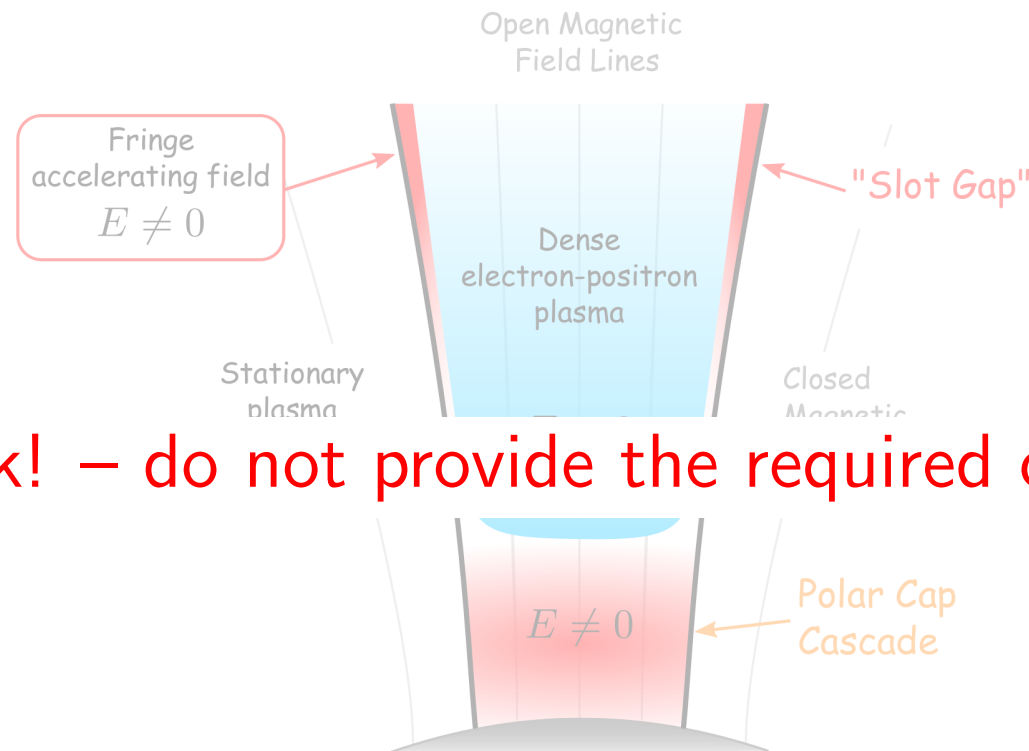


# Stationary cascades

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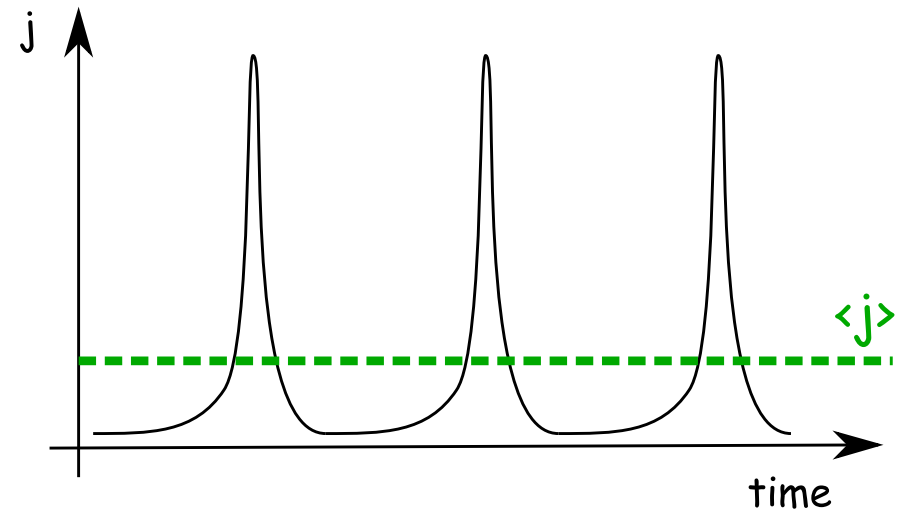
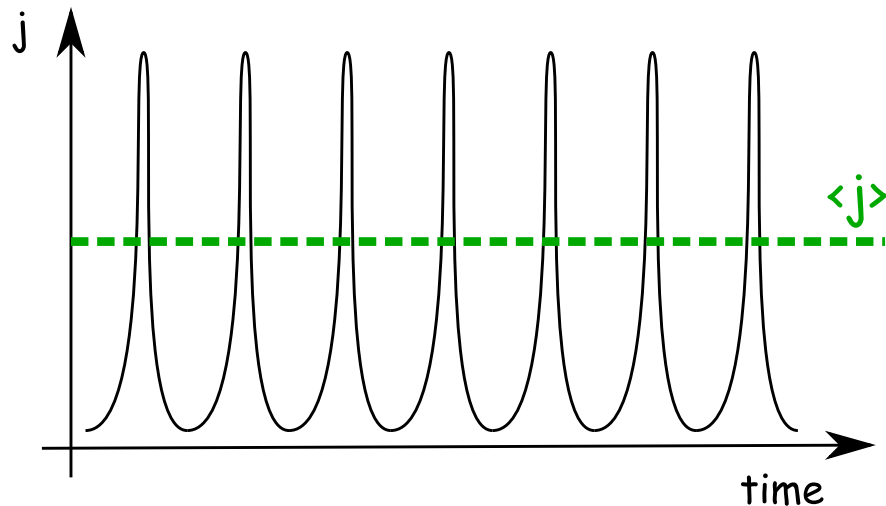
Predictions:

- Current density is almost equal to the Goldreich-Julian current density
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# Why can non-stationarity help?

magnetosphere timescales (seconds)  $\ll$  cascade time scales (microseconds)

**only time-average current density matters**



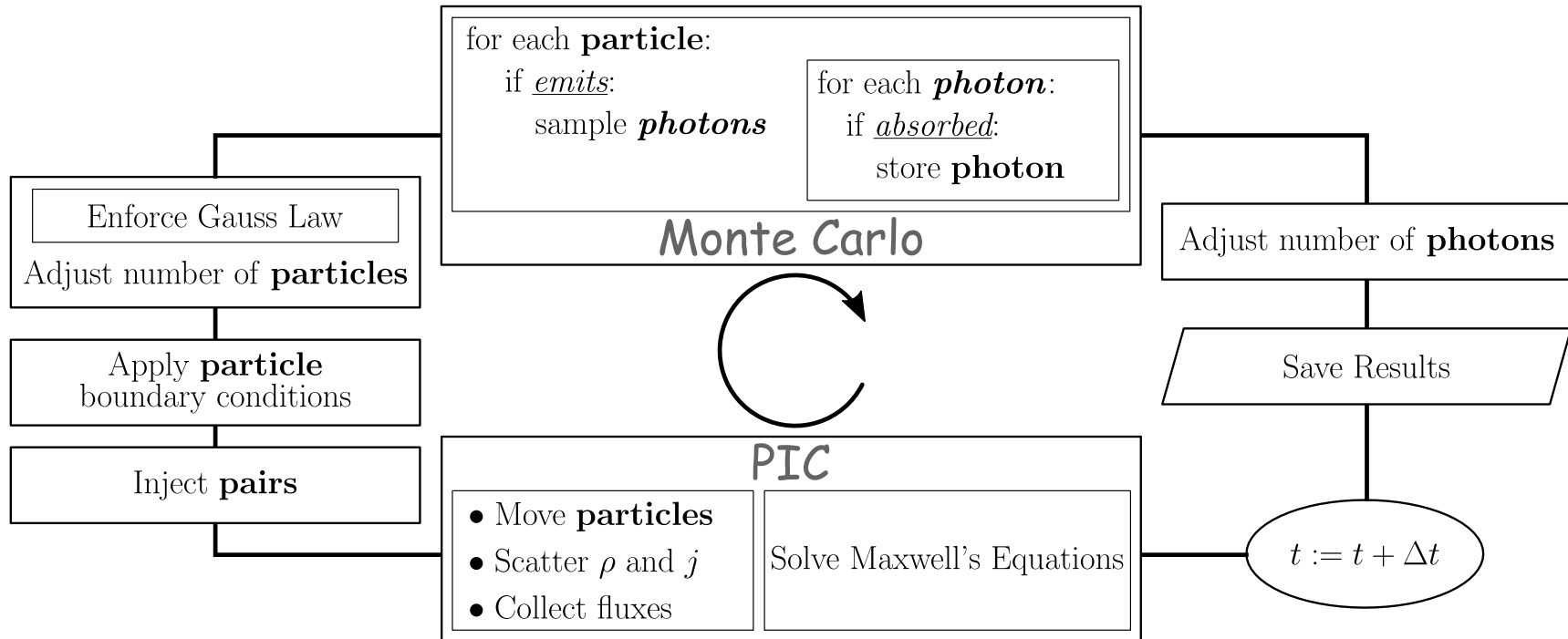
# Self-consistent modeling of electron-positron pair cascades

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What to model:

1. particles are accelerated by the electric field
2. particles emit gamma-rays
3. gamma-rays propagate some distance, are absorbed in the strong magnetic field and create electron-positron pairs
4. redistribution of charged particles changes the accelerating electric field
5. electrodynamics must be right:
  - ☐ electric field due to NS rotation
  - ☐ electric field due to charged particles distribution
  - ☐ *the average current density is set by the magnetosphere*

# Code structure



Particle acceleration  $\leftrightarrow$  Electric field

Particles  $\rightarrow$  Photons  $\rightarrow$  Particles(Pairs)

PIC

Monte Carlo

# Physical model

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**Ruderman-Sutherland model:** no particles can be extracted from the NS surface – the simplest possible model

1D approximation should work perfectly for this problem.

## SETUP

- **1D Electrostatic model**

$$\partial_t E_{\parallel} = -4\pi(j - j_0)$$

$j_0 = c \nabla \times \mathbf{B}$  – the current density required by the magnetosphere

- **gamma-ray production:** Curvature radiation
- **pair creation:** single photon absorption in dipole magnetic field

# Phase portrait of the cascade

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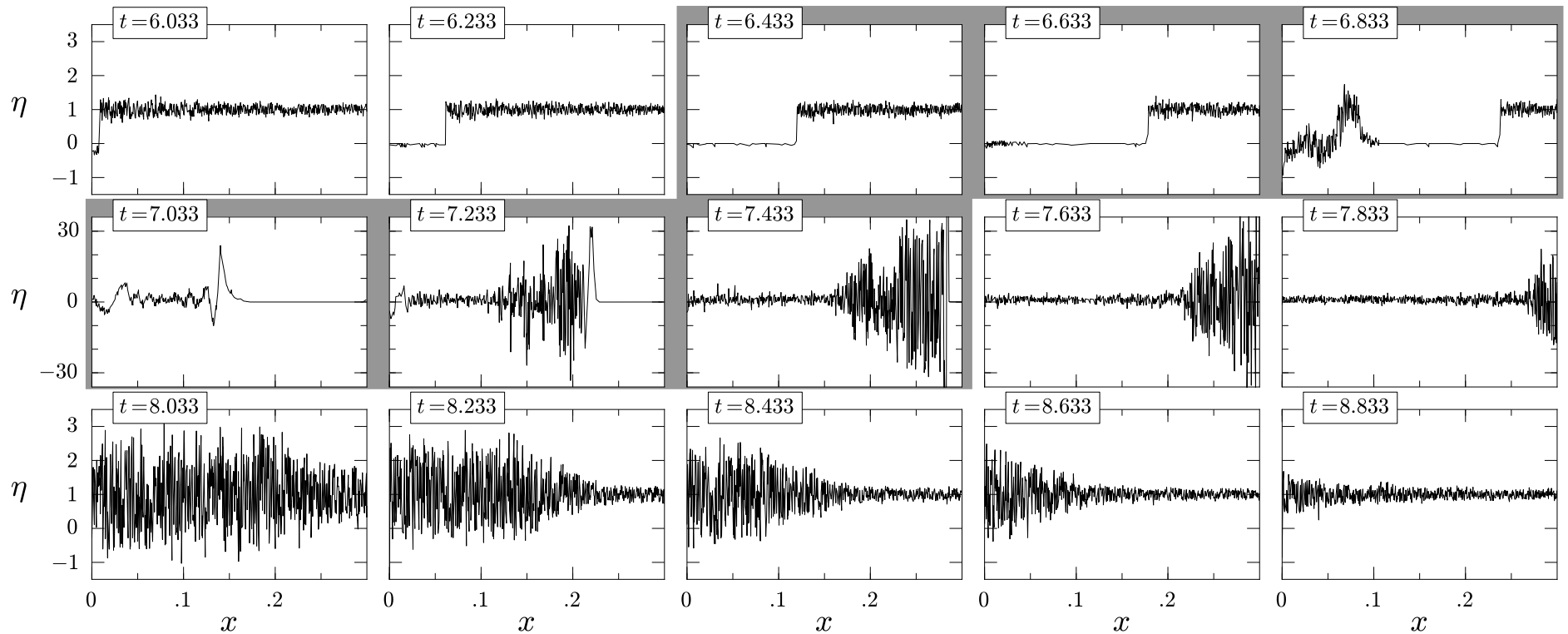
(xp\_jp1\_s1.avi)

# Charge density $\eta$

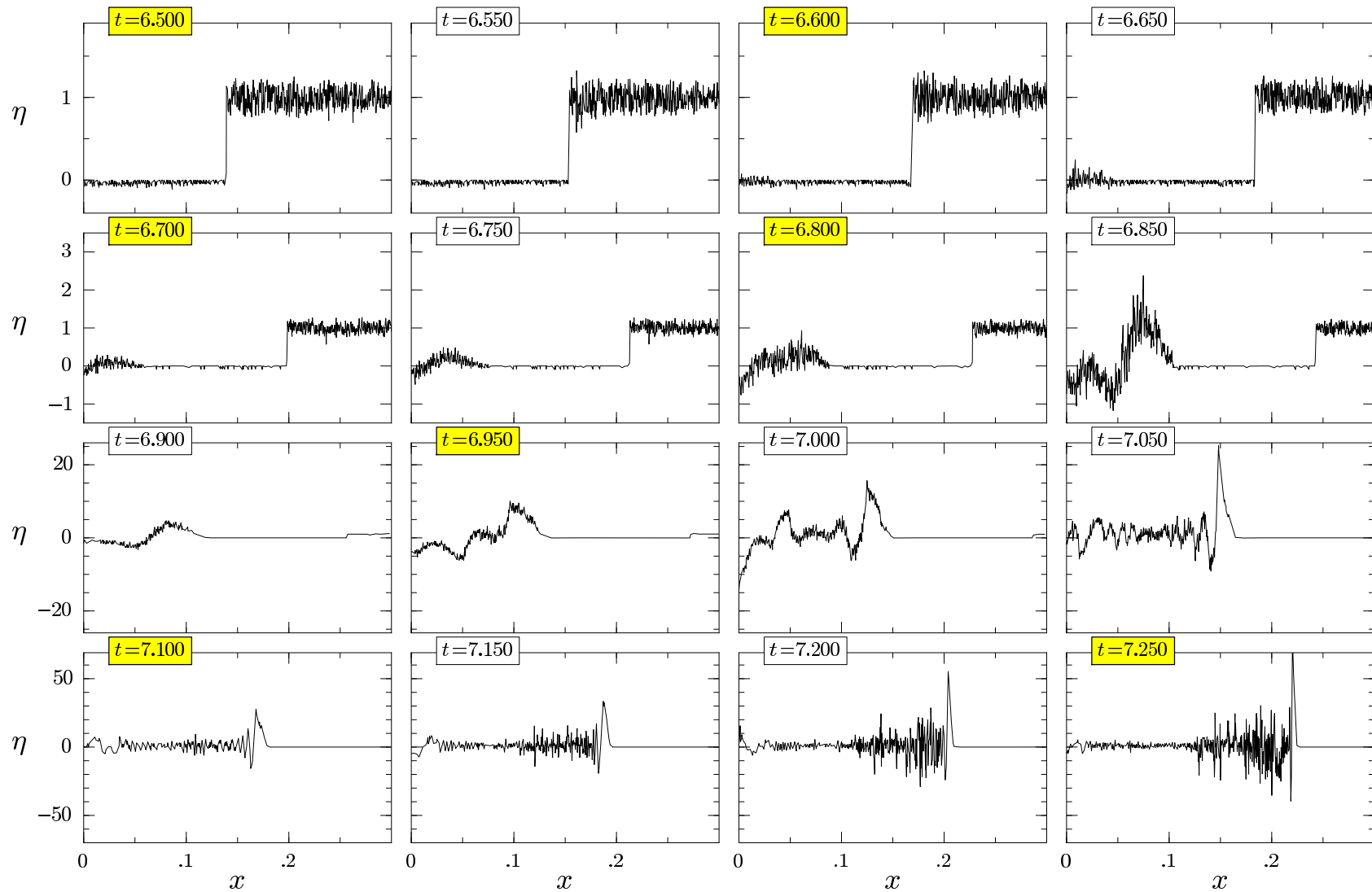
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(rho\_jp1\_s1.avi)

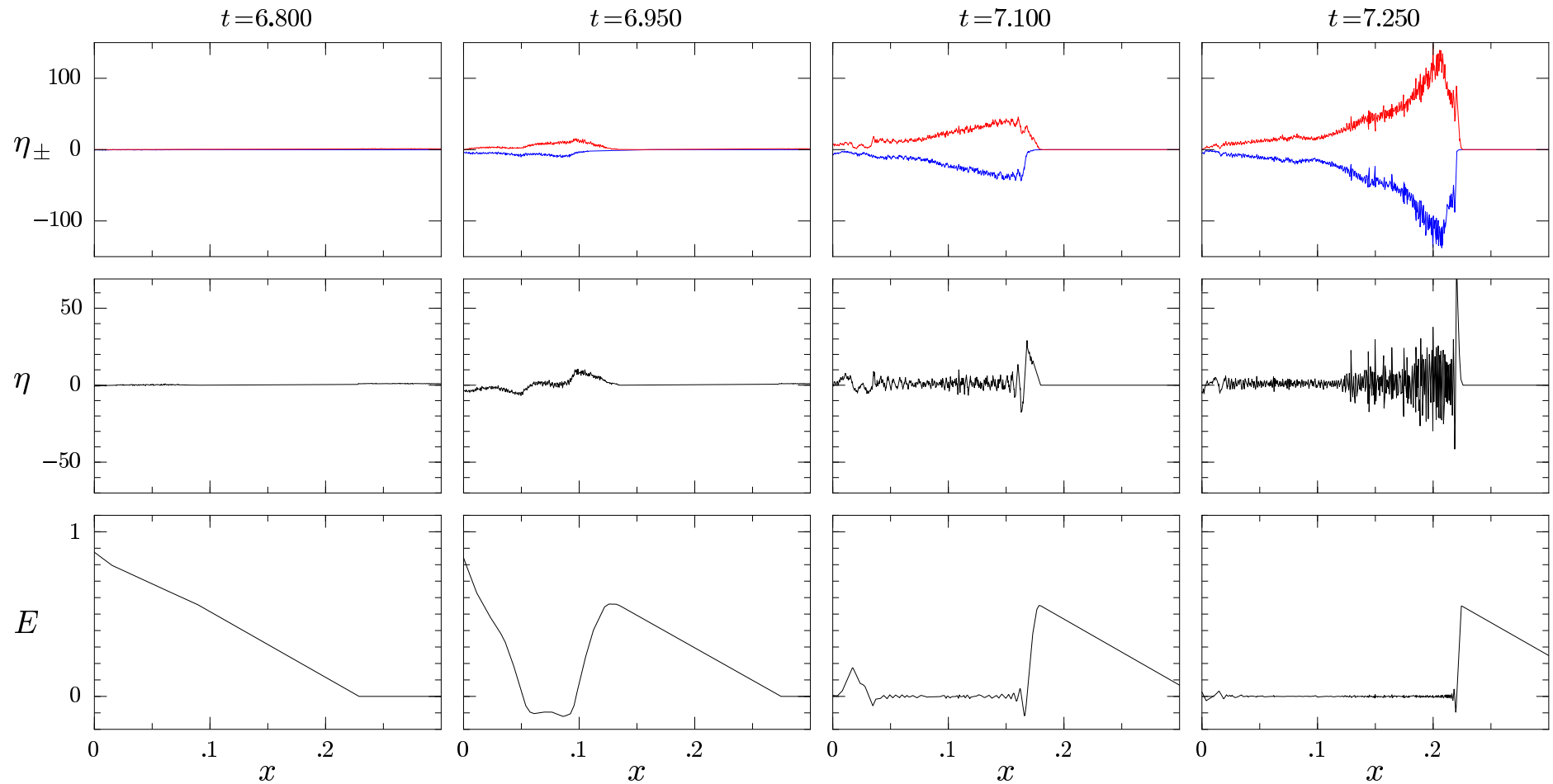
# Cascade development: full cycle



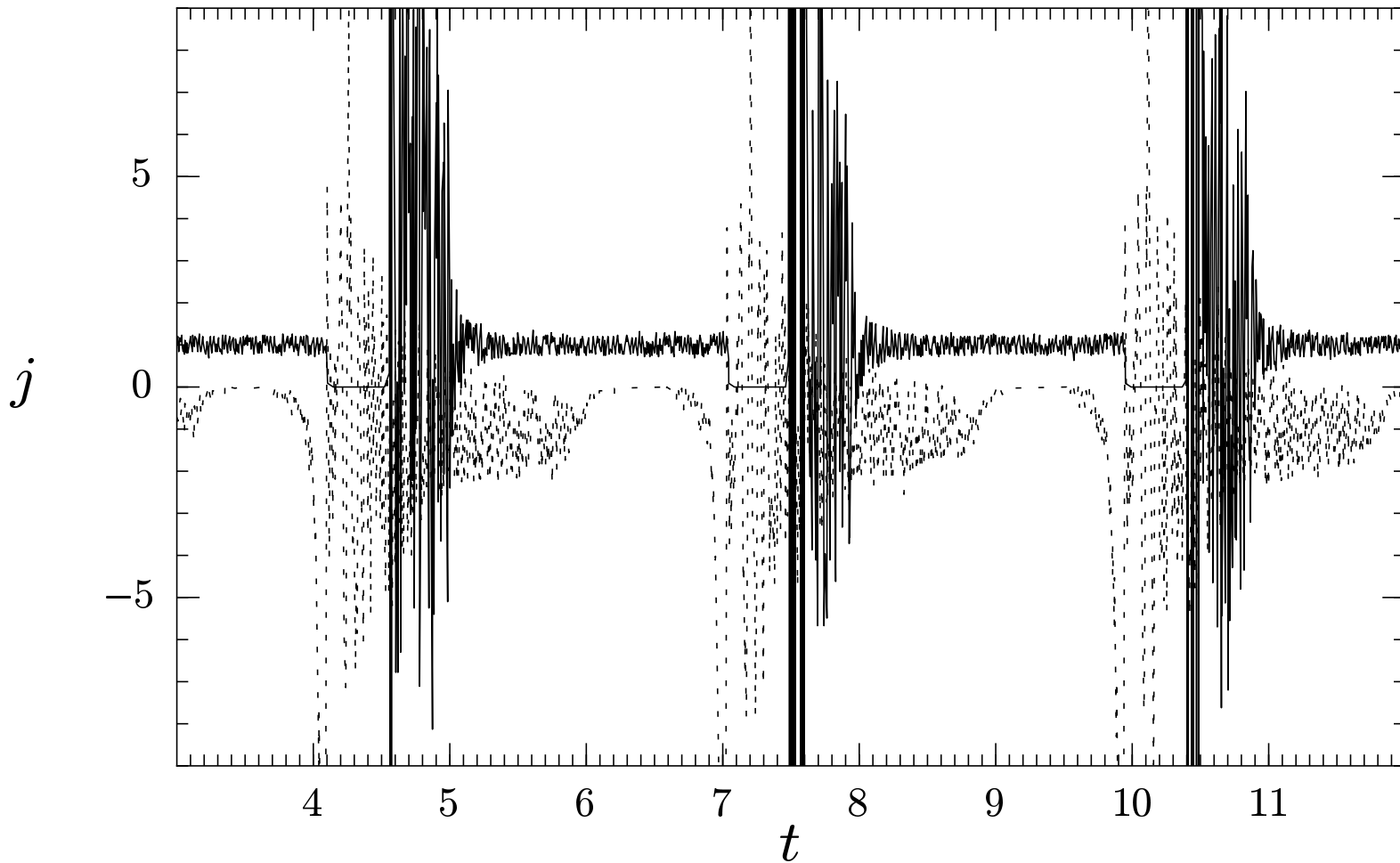
# Cascade development: plasma blob formation



# Cascade development: what is going on



## Current adjustment: $j = j_{\text{GJ}}$

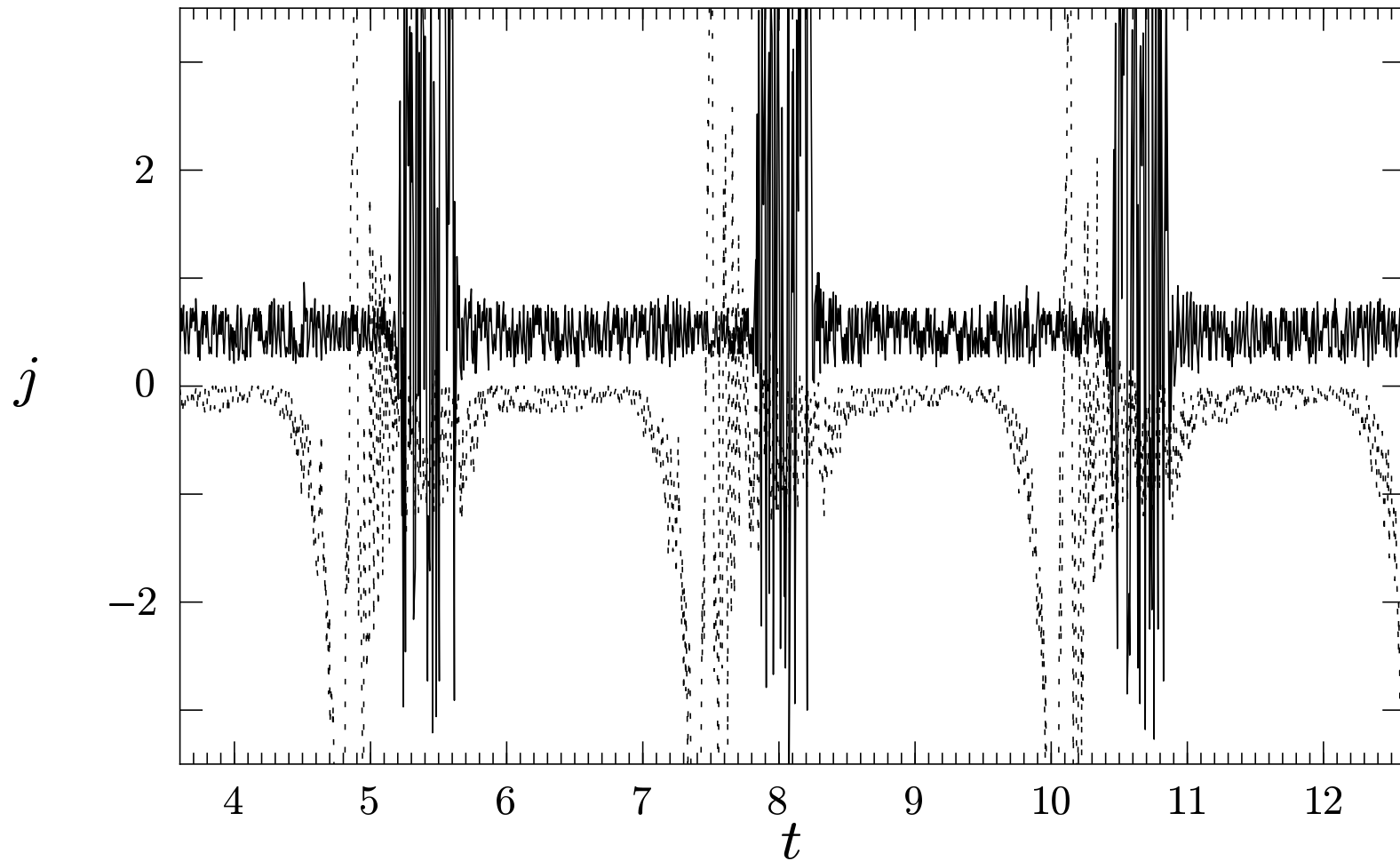


**Charge density:**  $j = 0.5 j_{\text{GJ}}$

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(rho\_jp0.5.avi)

## Current adjustment: $j = 0.5 j_{\text{GJ}}$

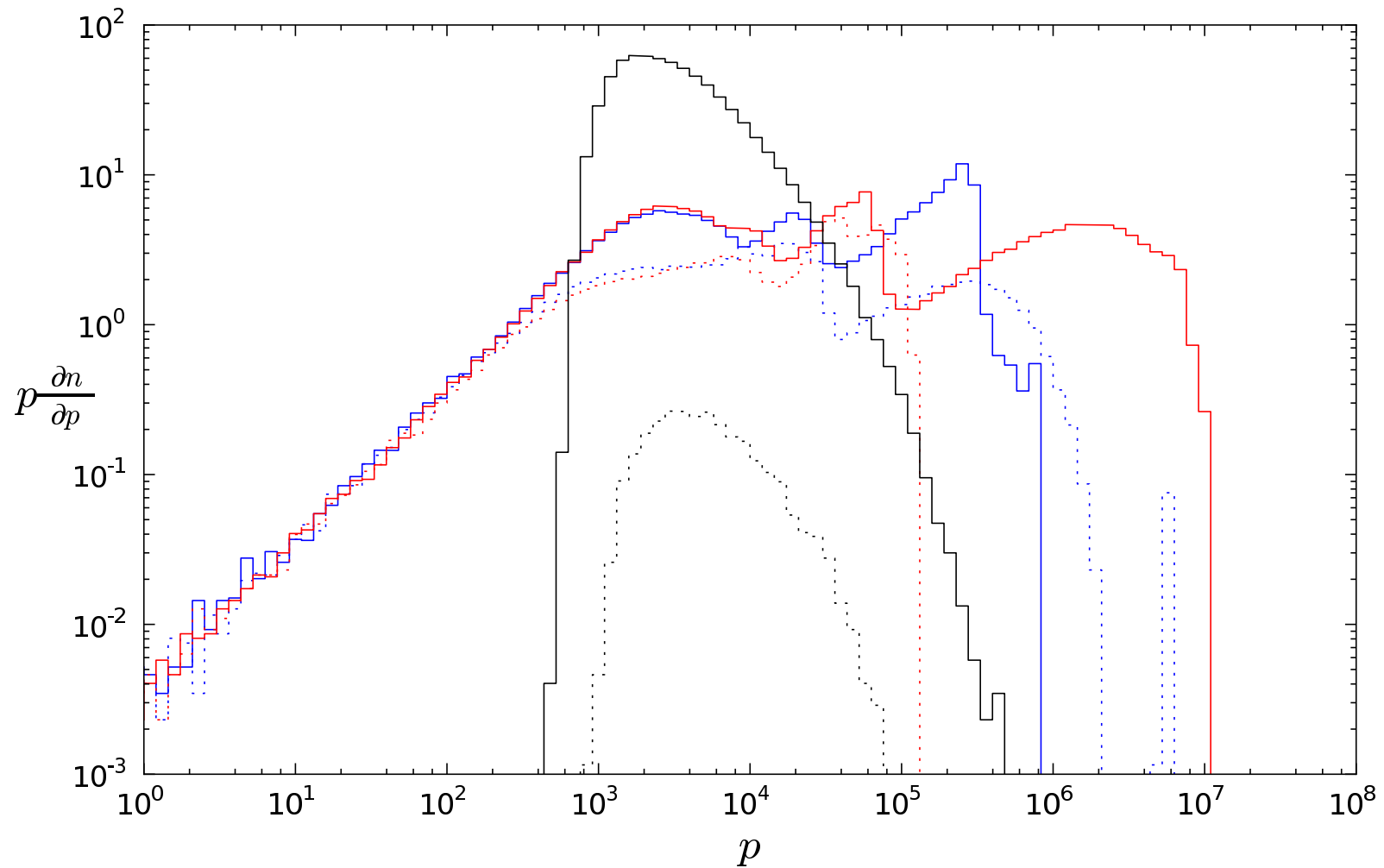


# Particle “thermalization”

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(xp\_track\_jp1\_1e4.avi)

# Particle energy distribution



# Superluminal wave: charge density

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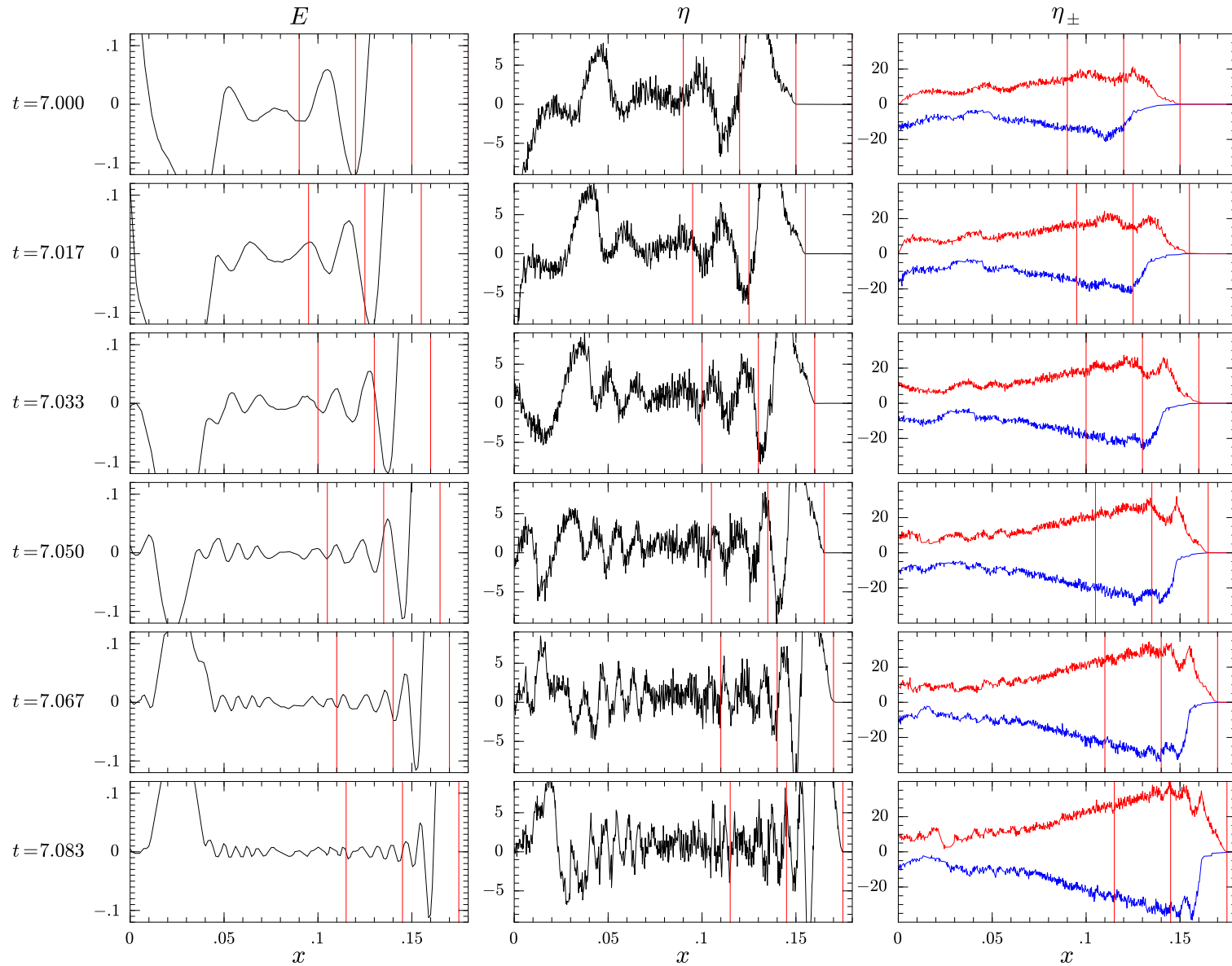
(rho\_wave\_propagation.avi)

# Superluminal wave: particle number density

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(ep\_wave\_propagation.avi)

# Superluminal wave: overview



# Summary

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- cascade can indeed support any current density
- cascade is self-sustaining, showing sort of a “limit cycle” behavior with two characteristic time scales
- cascade fills open magnetic field lines region with plasma with no gaps
- a population of low energy particles is created in each discharge
- plasma is 4-component  $\Rightarrow$  two fluid approximation does not work
- coherent superluminal wave is generated in each discharge
- energetics of each discharge is larger than predicted by Ruderman & Sutherland